The Neutrino Landscape

We have come a long way since the Solar Neutrino Problem still much to do

Bright Future: see "Neutrinos" White Paper

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Workshop on the Intermediate Neutrino Program

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Neutrino Masses & Mixing: The Heroic Years

R. Davis (BNL Chemist) – The Solar Neutrino Problem

~1/3 expected solar ν_e flux

>30 yr. ***Homestake*** Effort

Kamiokande & IMB Collaborations – ***Supernova 1987A*** &

Hints of Atm. ν_μ osc. (depletion)

M. Koshiba (Super Kamiokande) finds ν_μ-ν_τ atm osc. Large!

SuperK, ***SNO***, ***Kamland***, Gallium Exps,..K2K, MINOS, T2K

Daya Bay, RENO, Double Chooz… ***Neutrino Osc. Matures***

Large 3 Generation Mixing Paradigm Cofirmed!

$|\Delta m_{32}^2|$ & Δm_{21}^2 determined!

3 Generation Mixing Formalism

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix} \tag{1}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta. \tag{2}$$

Current Neutrino Mass & Mixing Parameters

- **$\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\, 2.4(1)\times 10^{-3}\ eV^2$**
  (atmospheric, beam & reactor all precise & consistent!)
- **$\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.5(2)\times 10^{-5}\ eV^2$** (Solar, Kamland)

$|\Delta m_{21}^2/\Delta m_{32}^2 \approx 1/30| \rightarrow$ CP Violation Exp Doable!

Hierarchy $m_3 > m_1$&m_2(normal) or $m_3 < m_1$&m_2(inverted)?

Large Mixing!

$\theta_{23} \sim 38\pm1°$ $\sin 2\theta_{23} \approx 0.97(1)$ (θ_{23} or $90° - \theta_{23}$) (atm.)

$\theta_{12} \sim 34\pm1°$ $\sin 2\theta_{12} = 0.93(2)$ (solar)

$\theta_{13} \leq 9.0\pm0.5°$ $\sin 2\theta_{13} = 0.31(1)$ (reactor)

$0 \leq \delta \leq 360°$? (some recent sensitivity)

$J_{CP} \sim 0.03\sin\delta$ (potentially large!) CKM$\sim 2\text{x}10^{-5}$

3 Generation ν_μ-ν_e Oscillations

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e)$$
$$+ \ \text{matter} \ + \text{smaller terms}$$

$$\mathbf{P}_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

$$\mathbf{P}_{II}(\nu_\mu \to \nu_e) = \tfrac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

$$\mathbf{P}_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

For antineutrinos, $\delta \to -\delta$ and opposite matter effect.

CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \qquad (3)$$

To leading order in Δm^2_{21} ($\sin^2 2\theta_{13}$ is not too small):

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects} \qquad (4)$$

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2_{CP} N}{1 - A^2_{CP}} \qquad (5)$$

N is the total number of $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ events.Since N falls (roughly) as $\sin^2\theta_{13}$ and $A^2_{CP} \sim 1/\sin^2\theta_{13}$, to a first approximation the F.O.M.is independent of $\sin\theta_{13}$. Similarly, given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A^2_{CP}.

CP Violation Insensitivities

- To a very good approx., our statistical
  ability to determine δ or A_{cp} is **independent** of $\sin^2 2\theta_{13}$ (down to ~ 0.003) and the detector distance L (for long distance).

  It turned out $\sin^2 2\theta_{13} \approx 0.1$!
  about 2-3 times larger than assumed in early studies
  precision θ_{13} & δ determination easier!
  Smaller A_{CP} Might help some systematics

What do we still need to learn?

1. **Sgn Δm_{32}^2?** (Important for Neutrinoless $\beta\beta$ Decay)
   Earth Matter Effect (SM or "New Physics")
   or Reactor Precision (Possible Near Term)

- 2. **Value of** δ?, J_{CP}?, CP Violation? ***(Holy Grail)***
  Relationship to Leptogenesis

- 3. **Precision** Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, $\boldsymbol{\theta_{13}}$ (better than 1%!)
  Redundancy & neutrinos vs antineutrinos
  Unitarity Violation? – Sterile neutrino Mixing
- 4. **"New Physics"** - Sterile ν, ***Very Weak*** Long/Short
  Distance New Physics (*The Dark World?*)…

CP Violation Requirements & LBNF

- What does it take to measure δ to $\pm 15°$ in about 6 yrs.?

  Answer (Approx.): 200kton Water Cerenkov Detector

  Approx 20% Acceptance qr

  40 kton LArgon 90% Acceptance

  or Hybrid combination

  + Traditional Horn Focused ν_μ WBB (0.5-5GeV)

  powered by

  1-2MW proton accelerator

  Long Distance > 1000km

Other approaches eg. Neutrino factory, low energy beams…

Exp. Goals: LBNF & Near Term Efforts

- ***Measure Leptonic CP Violation & phase δ***

  Our Origin (Leptogenesis Matter-antiMatter Asy.)

  Determine (Precisely) Neutrino Mass & Mixing Parameters

  Redundant Comparison Tests (Unitarity)

  Understand Pattern (Underlying Symmetry eg A4)

  Search for "New Physics" eg very weakly coupled new long or short distance effects (in Matter) vs MSW

  Search for Sterile Neutrinos (small mixing)

Other Physics

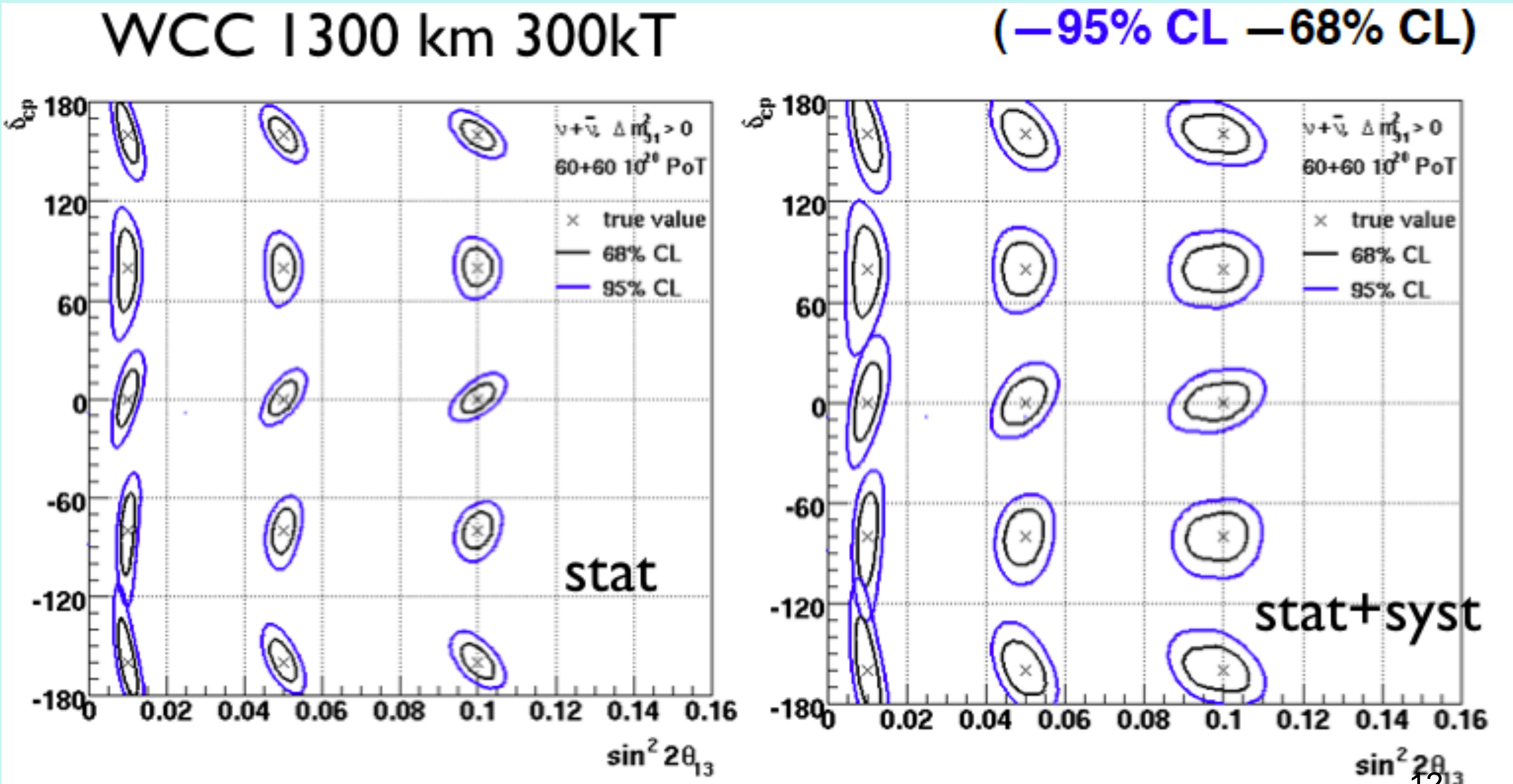
- ***Atm. vs Beam Neutrino Oscillations***
- ***Supernova Neutrinos (Relic & New),***
- ***Proton Decay (B-L=0)… Neutron-antiNeutron Osc. $\Delta B=2$***

Broad Revolutionary Discovery Potential

Big Underground Detectors Originally Proposed for Proton Decay Searches Motivated by Grand Unification

Facility for Revolutionary Discoveries

CP Phase & θ_{13} LBNF Sensitivity



Δm^2_{32} and $\sin^2 2\theta_{32}$ can be measured in long baselines as functions of E_ν (also obtained from atmospheric ν).

$\nu_\mu \to \nu_\mu$ & anti$\nu_\mu \to$antiν_μ Comparison

Usually phrased as a test of CPT (true in vacuum)

Apparent CPT violation → "New Physics" in ν interactions
(in matter) $\varepsilon\sqrt{2}G_F \nu\gamma_\mu\nu' f\gamma^\mu f$, f=e, u, d
Potential changes sign $\nu_\mu \to$antiν_μ
Sterile Neutrinos? etc

Goals

Long Term: CP violation in neutrino oscillations

LBNE: 1300km, WBB, 1-2MW, 40kton LAr, 10yrs

Proton Decay (10^{35}yr)

Similar Detector Requirements (Fortuitous)

Also: Atm & supernova ν, neutron-antineutron osc.,…

Nearer Term & LBNF

Sgn Δm_{32}^2? (Important for Neutrinoless ββ Decay)

Precision Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, θ_{13} (goal? ±1%!)

"New Physics" - Sterile ν, *Very Weak* New Interactions…Neutrino-antineutrino differences?

Anticipate (Hope For) Surprises

Lessons Learned for Future Neutrino Experiments

- Understand all backgrounds before starting
  (Recent experiments very good)
- Over design detector and its capabilities if possible
  (little room for descoping)

Definitive goals: eg. Sterile neutrino sensitivity

Start as soon as possible (long time commitment)